The effect of immunization against gonadotropin-releasing factor on growth performance, carcass characteristics and boar taint relevant to pig producers and the pork packing industry: A meta-analysis

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A B S T R A C T

Meta-analysis was used to compare pigs immunocastrated (IC) with Improvac® versus physically castrated (PC) or entire male (EM) pigs. Performance and carcass data as most relevant for producers and packers were analyzed and the risk of boar taint was assessed by comparing the number of pigs exceeding the consumer thresholds of detection (ToD) for skatole and androstenone.

A total of 78 articles fulfilled pre-defined inclusion criteria. Compared to PC pigs, IC pigs have a higher average daily gain (ADG; $+32.54\,g/day$, $P < 0.0001$) and more favorable feed conversion ratio (FCR; $-0.234\,kg/kg$, $P < 0.0001$), higher live weight and percentage lean, and lower hot carcass weight (HCW) and dressing percentage. Compared to EM pigs, IC pigs have a higher ADG ($+65.04\,g/day$, $P < 0.0001$), FCR ($+0.075\,kg/kg$, $P < 0.0001$), live weight and HCW, and a similar dressing percentage.

Conventionally raised IC pigs yield more valuable meat compared to PC ($+0.628\,kg$) and EM ($+1.385\,kg$) pigs. Heavy IC pigs (HCW $> 97.7\,kg$) destined for the production of high-quality cured products gain approximately $0.3\,kg$ more ham than their PC counterparts, with backfat and intramuscular fat still fulfilling the requirements for high-quality cured products.

The risk of exceeding the ToD for skatole and androstenone is similar in IC and PC pigs, but significantly higher in EM pigs.

Results from our meta-analyses confirm growth performance advantages of IC pigs compared with PC or EM pigs, and reveal a higher gain of valuable meat and a similar risk of boar taint as estimated for PC pigs.

1. Introduction

Physical castration of male piglets is a traditional practice to avoid boar taint, an unpleasant odor and flavor of meat from entire male (EM) pigs. Boar taint has been mainly attributed to the presence of androstenone and skatole. The sexual steroid androstenone is produced in the interstitial tissue of the testes. Accordingly, the level of androstenone is directly influenced by the activity of the testes and increases dramatically with puberty. Skatole is produced in the large intestine by microbial breakdown of the amino-acid tryptophan. The metabolism of skatole in the liver is reduced by sexual steroids, resulting in increased accumulation in the fat in male pigs as the testes start to produce more testosterone at puberty (Mackinnon and Pearce, 2007a).

Physical castration is, however, a painful and stressful procedure to the piglets (Prunier et al., 2006). Therefore, physical castration without analgesia or anesthesia has been banned in many countries.

As an alternative to physical castration immunocastration has become available. The first vaccine against the gonadotrophin releasing factor (GnRF) was launched in 1998 in Australia and New Zealand (Mackinnon and Pearce, 2007b) and has been subsequently released in numerous countries all over the world (Improvac®, Improvest®, Vivax®, Innosure®; from here forward referred to as Improvac®).

Male pigs are given Improvac® twice: the first dose is administered after 8 to 9 weeks of age and the second dose is given a minimum of 4 weeks after the first dose and between 4 and 6 weeks before slaughter, although in some markets the latter timing may be from 3 to 10 weeks before slaughter. The first dose primes the pig's immune system, but does not cause any relevant physiological change in the animal. The second dose creates the effective immune response, stimulating the immune system to produce specific antibodies resulting in a

suppression of testicular function. The hormonal status rapidly adjusts to resemble that of a barrow (Dunshea et al., 2013). As a result, male pigs do not have to experience the pain and stress associated with physical castration and additionally are able to fully express their inherent potential for feed-efficient growth for the majority of their production cycle as an EM, before the effect of immunocastration applies. The productivity advantages of raising EM pigs compared to physically castrated (PC) pigs mainly include improved feed efficiency, less backfat and leaner carcasses (Xue et al., 1997).

Numerous studies have been conducted, evaluating different aspects of immunocastration such as performance parameters and carcass characteristics or the risk of boar taint. In brief, immunocastrated (IC) pigs grow faster and have a better feed conversion ratio than PC pigs. Compared to EM pigs, IC pigs consume more feed and also grow faster. IC pigs have a lower carcass yield than PC pigs and EM pigs, whereas lean meat percentage is intermediate (see review from Millet et al., 2011). Immunocastration significantly reduces androstenone and skatole levels in fat compared with EM pigs, and sensory studies confirmed that Improvac® effectively and consistently reduces the risk of boar taint (see review from Mackinnon and Pearce, 2007a).

Additionally, statistical analyses have been conducted, which combine results from different studies and focus on different key aspects: Trefan et al. (2013) put emphasis on the effect of gender on pork quality parameters, whereas Harsh et al. (2017) and Pauly et al. (2012) assessed carcass and pork quality parameters. The most widespread meta-analysis from Batorek et al. (2012a) evaluated the effect of immunocastration on production performance, carcass traits, meat quality, reproductive organs and boar taint compounds.

The aim of our study was not only to update previous meta-analyses with studies published until end of first quarter 2017, but also to focus the analyses on aspects most relevant for the stakeholder groups of pig producers and the pork packing industry, respectively. The following research questions were defined in advance of the study:

1) What is the effect of immunocastration compared to physical or no castration of male pigs on performance and carcass data most relevant for the producers and how are these parameters influenced by (a) the feed additive ractopamine, (b) the pork production system, i.e. raising light, medium or heavy pigs, and (c) the time between the 2nd GnRF immunization (V2) and slaughter? (In the following 'producer's perspective'.)
2) What is the effect of immunocastration compared to physical or no castration of male pigs on carcass data most relevant for the packers, while differentiating between (a) conventional pork production and (b) pork destined for the production of high-quality cured products, and how are these parameters influenced by ractopamine or the pork production system? (In the following 'packer's perspective'.)
3) What is the risk of boar taint in meat from IC pigs compared to meat from PC or EM pigs as evaluated by (a) objective, i.e. quantitative measurements and (b) subjective sensory assessment? (Results can be regarded as relevant for both stakeholder groups.)

These research questions constituted the basis for the definition of inclusion criteria.

2. Materials and methods

2.1. Data search

An electronic database previously developed by the company marketing Improvac® (Zoetis) served as the source of literature. The database included all publications identified for Improvac® and contained 305 articles at the time of study initiation (second quarter of 2017). Studies were not restricted to English language and were derived from peer-reviewed papers, congress proceedings, and grey literature. In order to ascertain the completeness of the database, bibliographies of

relevant articles, meta-analyses and literature reviews were searched for potentially missing papers.

The following eligibility criterion was applied to identify studies for further evaluation: any article reporting comparative efficacy of immunocastration with Improvac® versus physical castration or no castration of male pigs. All studies were eligible, regardless of the reporting of randomization or blinding or of the level of scientific credibility (peer-reviewed and non peer-reviewed articles). The latter, however, was recorded in order to assess any impact of study credibility on the results. Review articles or meta-analyses were not considered for inclusion, but used to assess completeness of database.

Inclusion criteria varied according to the research questions defined in advance.

2.1.1. Inclusion criteria and data extraction for analyses relevant from the producers' perspective

In order to answer the research question defined for the pig producers, articles were included which reported average daily gain (ADG) AND [feed conversion ratio (FCR) OR feed efficiency (FE)] AND [live weight at slaughter OR hot carcass weight (HCW)]. ADG and FCR as reported for the entire observation period were used for the analyses. Results reported for FE were calculated to FCR, using the following formula: $FCR = 1/FE$. In order to allow for additional subgroup analyses, the potential use of the feed additive ractopamine as well as the time between V2 and slaughter (IC pigs) were recorded, and studies were categorized according to the pork production system (light, medium, or heavy pig production).

If reported in the included studies, dressing percentage, percentage lean, and backfat thickness were also collected for analyses.

2.1.2. Inclusion criteria and data extraction for analyses relevant from the packers' perspective

Separate searches were run to identify articles reporting data from conventional pork production and pork production destined for high-quality cured products.

Studies of conventional pork production were included if the following parameters were available: weight of ham AND weight of loin AND weight of shoulder AND weight of belly AND (live weight at slaughter OR HCW). The latter allowed for subgroup analyses of the pork production system. Additionally, the use of ractopamine was recorded. For analyses relevant for the pork production destined for high-quality cured products the following inclusion criteria applied: studies reporting weight of ham AND percentage intramuscular fat AND backfat thickness AND (live weight at slaughter OR HCW). Although not an inclusion criterion, dressing percentage was also recorded if available. Pork production for high-quality cured products requires a reasonably high fat content (minimal backfat thickness of 20 mm and 2.5% intramuscular fat (IMF) for European production (Morales et al., 2011a)); therefore, no use of ractopamine, which improves carcass leanness, was expected even in those countries where ractopamine use is permitted. Accordingly only one subgroup analysis on the weight classification was foreseen. In addition to the comparative analyses, absolute values of backfat thickness and IMF were used to assess if the minimum requirements were fulfilled.

2.1.3. Inclusion criteria and data extraction for boar taint analysis (relevant from both perspectives)

Separate searches were run to identify articles reporting objective measurements of level of boar taint compounds in fat and subjective sensory evaluations of pork meat or fat. For the analysis of objective measurements, studies had to report the number or proportion of pigs exceeding at least one of the following thresholds of consumer detection as defined for the main boar taint compounds: skatole threshold: 0.2 μg/g fat (Dunshea et al., 2001); androstenone intermediate threshold: 0.5 μg/g fat (Dunshea et al., 2001; Andresen, 2006) and androstenone high threshold of detection: 1.0 μg/g fat (Dunshea et al.,

2001; Andresen, 2006).

For the subjective measurement of boar taint, sensory tests of odor OR flavor OR overall acceptability/liking of samples from IC pigs and comparator pigs were included. Studies had to report the type of panel (experts or consumers) as well as the comparative outcome and its statistical significance. No stratification according to the use of ractopamine was foreseen, as the feed additive has no impact on sensory characteristics (Juárez et al., 2016; Fernandez-Dueñas et al., 2008).

2.2. Data analysis

2.2.1. Meta-analysis

Meta-analyses were conducted for the defined parameters using the statistical software Comprehensive Meta-Analysis V. 2.2 (Biostat, Englewood, NJ). The raw mean difference between IC pigs and comparators was calculated for all performance and carcass parameters. For the analysis of the number of pigs exceeding the threshold of detection of boar taint compounds the absolute risk difference was used as effect size. For meta-analyses including > 3 comparisons the random-effects model was chosen to account for variation across studies, thereby assuming that the true effect size is not the same in all studies. If the number of studies was small ($n \leq 3$), a fixed-effect model was used, because the random-effects model does not provide accurate results if the number of studies is small (Borenstein et al., 2009). For the evaluation of heterogeneity between subgroups, a mixed-effects model was applied unless at least one subgroup included ≤ 3 studies, when a fixed-effect analysis was used.

Several sub-group analyses were conducted in a predefined sequence. For comparisons including both peer-reviewed and non peer-reviewed articles, a first subgroup analysis assessed differences in outcomes between both. In case of no statistically significant differences ($P \geq 0.05$ between subgroups), all studies were considered for further analyses.

The second subgroup analyses differentiated between comparisons including pigs fed ractopamine, and those not allowing the feed additive.

The following subgroup analyses were conducted on studies without ractopamine only. Subgroup analyses were run for the pork production system (light, medium, or heavy pork production) for all performance and carcass parameters. The carcasses were categorized according to Harsh et al. (2017) as light (HCW < 90.9 kg), medium (90.9 kg $\leq$ HCW $\leq$ 97.7 kg), or heavy (HCW > 97.7 kg).

Subgroup analyses of the time between V2 and slaughter were run for all performance and carcass data as relevant for the producers. Two time periods were defined with a cutoff point at 4.5 weeks for the period between V2 and slaughter (time period < 4.5 weeks and ≥ 4.5 weeks).

For each parameter Z statistic and corresponding P-values were used to determine if differences between IC pigs and comparator were statistically significant (Borenstein et al., 2009). In accordance with other meta-analyses (De la Cruz et al., 2017; Batorek et al., 2012a) the I^2 statistic was used to describe the percentage of total variation across studies, as recommended by Higgins et al. (2003). Statistical significance was declared based on two-tailed tests at $P < 0.05$.

2.2.2. Descriptive analysis

Results from subjective sensory tests of pork meat were analyzed using a descriptive approach. Sensory tests were conducted using different scales and measurements with little statistics reported (mainly differentiating between $P < 0.05$ and $P \geq 0.05$ only), and therefore did not qualify for meta-analysis. In accordance with Allison et al. (2009a) studies were classified according to their comparative rating, i.e. if samples from IC pigs were assessed as being superior, equal or inferior compared to those from PC or EM pigs. Evaluated were the sensory assessment of odor, flavor and overall acceptability/liking.

Results were analyzed separately for expert and consumer panels.

Studies used different cooking or melting methods. Variability, however, did not allow for the definition of a limited number of rational subgroups. Accordingly, all studies were analyzed regardless of the heating method used.

2.2.3. Additional analysis

In order to assess the overall gain of valuable meat (from the perspective of the packers), the weight differences for ham, shoulder, loin, and belly were added. The calculations were performed for all comparisons as well as for comparisons excluding studies with ractopamine and being restricted to medium and light pork production systems (HCW $\leq$ 97.7 kg). Both calculations were performed twice: first of all, only weight differences for ham, shoulder, loin, or belly were considered if statistically significant. In case of non-statistically negative results for IC pigs, the overall gain was re-calculated considering also these negative results, thereby representing the most conservative approach.

3. Results

A total of 78 articles fulfilled at least one of the defined inclusion criteria (number already adjusted to duplicates), including in total 16,937 pigs (IC pigs $n = 7921$; PC pigs $n = 6692$; EM pigs $n = 2324$). In the case that the same study was published in a peer-reviewed and non peer-reviewed paper (e.g. congress proceeding), only the article of highest scientific reputation was included. Fourteen articles fulfilled inclusion criteria for more than one perspective.

When several studies were reported within an article, they were considered as separate comparisons. The articles allowed the extraction of 66 comparisons from the perspective of the producers (37 comparisons versus PC pigs and 29 comparisons versus EM pigs), 28 from the perspective of the packers (conventional pork production: IC versus PC pigs $n = 13$ and IC versus EM pigs $n = 10$; pig production for high quality cured products: IC versus PC pigs $n = 5$), and 86 comparisons from the 'combined perspective' (quantitative boar taint analysis: IC versus PC pigs $n = 20$ and IC versus EM pigs n = 20; sensory assessment of boar taint: IC versus PC pigs $n = 28$ and IC versus EM pigs $n = 18$). An overview of all studies included is provided in Table 1.

In the following, results will be reported separately for each perspective. All results are presented in Tables 2–6, additionally forest plots for all analyses (all comparisons, with and without ractopamine) are included in Appendix A (supplementary material).

3.1. Results from the perspective of the producers

3.1.1. Comparisons of IC pigs versus PC pigs

For all parameters under investigation there were no statistically significant differences between studies reported in peer-reviewed articles and studies reported elsewhere. Therefore all studies were considered for further analyses.

Over the entire observation periods, ADG was on average 32.54 g/day higher in IC pigs compared to PC pigs ($P < 0.0001$). The incremental ADG was higher in studies including pigs fed ractopamine, although the difference between studies in- and excluding ractopamine did not reach statistical significance ($P = 0.052$). Differences between the different pork production systems (light, medium, heavy) were observed, but there was no trend in one direction.

Feed conversion ratio over the entire feeding period was significantly lower in IC pigs, resulting in an average of 0.23 kg feed consumed less per kg body weight gained ($P < 0.0001$). Live weight was approximately 2 kg higher in IC pigs ($P = 0.018$). There were trends towards a higher difference in live weight of IC pigs not fed ractopamine, in medium and heavy pigs, and in studies with a period of ≥ 4.5 weeks between V2 and slaughter, as differences were statistically significant only in the mentioned subgroups. However, differences between the respective subgroups did not reach statistical significance

Table 1

Overview of studies and number of comparisons which fulfilled the inclusion criteria as defined for the analyses from the perspective of pork producers and packers, as well as for boar taint analyses.

Reference	Number of Comparisons								
	Producers' Persp.		Packers' Persp.			Boar Taint Analyses			
			Conv. Pork Prod.		HQCP	S + A Levels in fat		Sens. Assess.	
	IC vs. PC	IC vs. EM	IC vs. PC	IC vs. EM	IC vs. PC	IC vs. PC	IC vs. EM	IC vs. PC	IC vs. EM
Aleksić et al., 2012						1	1		
Allison et al., 2009b						1			
Aluwé et al., 2013								2	2
Andersson et al., 2012	2	2							
Asmus et al., 2014	3								
Batorek et al., 2012b	2	2							
Boghossian et al., 1995							1		1
Boler et al., 2014			2	2					
Boler et al., 2012			2						
Boler et al., 2011			4	4					
Braña et al., 2013	1		1					2	
Brunius et al., 2011						1	1		
Costa Lima et al., 2012								2	
D'Souza and Mullan, 2003								2	2
D'Souza and Mullan, 2002								1	
Dos Santos et al., 2012	1								
Dunshea et al., 2011	1	2							
Dunshea and McCauley, 2009							1		
Dunshea et al., 2001	2	2				1	1		
Einarsson et al., 2008						1	1		
Elsbernd et al., 2015	1	1							
Fàbrega et al., 2010	1	1							
Fernandez-Dueñas et al., 2016	1								
Font-i-Furnols et al., 2016							1		
Font-i-Furnols et al., 2012					1				
Font-i-Furnols et al., 2009								1	1
Font-i-Furnols et al., 2008								1	1
Fuchs et al., 2011	1								
Fuchs et al., 2009			1						
Furuya et al., 2011								1	
Ha et al., 2008						1			
Hemonic et al., 2009	1					1	1		
Hennessy et al., 2009a								1	
Hennessy et al., 2009b						1	1	1	1
Hennessy et al., 2006a	1					1			
Hennessy et al., 2006b								1	
Hennessy and Walker, 2004									1
Herrick et al., 2016								1	
Jaros et al., 2005						1			
Jeong et al., 2011								1	1
Jones-Hamlow et al., 2015								2	1
Kantas et al., 2014	1	1				1	1		
Kim et al., 2007	1	1							
Lealiifano et al., 2011		4					1		
Little et al., 2014								2	1
Lodge et al., 2008									1
Lowe et al., 2014a			2						
Lowe et al., 2014b	2								
Martinez-Macipe et al., 2016					1			1	
Medina et al., 2008	1								
Metz et al., 2002							1		
Miclat-Sonaco et al., 2008						1			
Molist et al., 2014	2	2							
Moore et al., 2017							1		1
Moore et al., 2009		3							
Morales et al., 2013	2				2				
Morales et al., 2011a	2				1				
Morales et al., 2011b	1								
Morales et al., 2010	1	1				1	1		
Needham and Hoffman, 2015				1					
Oliviero et al., 2016							1		
Pauly et al., 2010								2	2
Pauly et al., 2009	1	1	1	1		1	1		
Pearce et al., 2009						1	1		
Puls et al., 2014a	2	2							
Puls et al., 2014b	1								
Rikard-Bell et al., 2009		2		2					

Table 1 (continued)

Reference	Number of Comparisons								
	Producers' Persp.		Packers' Persp.			Boar Taint Analyses			
			Conv. Pork Prod.		HQCP	S + A Levels in fat		Sens. Assess.	
	IC vs. PC	IC vs. EM	IC vs. PC	IC vs. EM	IC vs. PC	IC vs. PC	IC vs. EM	IC vs. PC	IC vs. EM
Sattler et al., 2014						1	1		
Silveira et al., 2008								1	
Škrlep et al., 2016									1
Škrlep et al., 2012						1	1		
Škrlep et al., 2011	1	1							
Škrlep et al., 2010						1			
Spring et al., 2011								1	
Van den Broeke et al., 2016								1	1
Virgili et al., 2013								1	
Yang et al., 2009					1				
Zamaratskaia et al., 2008	1	1				1	1		
Total No. of Studies	26	17	7	5	4	20	20	21	15
Total No. of Comparisons	37	29	13	10	5	20	20	28	18

Persp. = perspective; Conv. Pork Prod. = conventional pork production; HQCP = high-quality cured products; S + A = skatole and androstenone; Sens. Assess. = sensory assessment; IC = immunocastrated; PC = physically castrated; EM = entire male.

(Table 2a and Fig. 1A).

Over all studies, HCW was lower in IC pigs (-0.87 kg; $P = 0.026$). Although the difference was no longer statistically significant in the different subgroups, the overall effect direction remained similar. Consistent with the lower HCW, dressing percentage was approximately 1.7% units lower in IC pigs compared to PC pigs ($P < 0.0001$). Although there were significant differences between the pork production systems (light, medium, heavy), there was no trend in one direction. Over all studies percentage lean was significantly higher in IC pigs (1.2% units, $P < 0.0001$), although no difference in lean meat could be found if pigs were fed ractopamine. Backfat thickness was consistently smaller in IC pigs (-2 mm; $P < 0.0001$). There was a numerically but not statistically significant trend towards a smaller difference in percentage lean and backfat thickness between IC and PC pigs in the subgroups with the longer interval between V2 and slaughter (Table 2b and Fig. 1A).

Table 2a
Results of meta-analysis of growth performance parameters as relevant for producers (raw mean differences between IC pigs and PC or EM pigs).

		IC versus PC					IC versus EM				
		n	RMD	P-Value	I-squared	P-Value between	n	RMD	P-Value	I-squared	P-Value between
ADG	Peer-reviewed studies	33	31.95	< 0.0001	62.7%	0.560	29	65.04	< 0.0001	63.4%	n.a.
(g/day)	Non peer-reviewed studies	4	45.56	0.044	91.4%		0				
	All comparisons	37	32.54	< 0.0001	79.6%		29	65.04	< 0.0001	63.4%	
	With ractopamine	5	91.09	0.006	74.3%	0.052	4	95.77	< 0.0001	0.0%	0.110
	Without ractopamine	32	26.30	< 0.0001	87.5%		25	59.40	< 0.0001	64.1%	
	HCW < 90.9 kg	13	32.43	0.009	63.2%	0.039	18	65.863	< 0.0001	46.7%	0.044
	HCW 90.9 to 97.7 kg	13	15.78	0.009	74.3%		5	51.061	0.027	84.8%	
	HCW > 97.7 kg	6	56.37	< 0.0001	46.6%		2	48.417	0.170	57.7%	
	V2 to slaughter < 4.5 w	11	32.95	0.020	63.8%	0.623	10	63.155	0.002	43.1%	0.836
	V2 to Slaughter ≥4.5 w	21	25.38	< 0.0001	77.1%		15	57.924	< 0.0001	71.8%	
FCR	Peer-reviewed studies	33	−0.237	< 0.0001	55.0%	0.697	29	0.075	< 0.0001	27.3%	n.a.
(kg/kg)	Non-peer-reviewed studies	4	−0.224	< 0.0001	0.0%		0				
	All comparisons	37	−0.234	< 0.0001	50.1%		29	0.075	< 0.0001	27.3%	
	With ractopamine	5	−0.310	< 0.0001	60.1%	0.120	4	0.103	0.001	0.0%	0.360
	Without ractopamine	32	−0.223	< 0.0001	42.7%		25	0.072	< 0.0001	34.7%	
	HCW < 90.9 kg	13	−0.232	< 0.0001	48.5%	0.305	18	0.067	0.003	15.6%	
	HCW 90.9 to 97.7 kg	13	−0.212	< 0.0001	50.7%		5	0.065	0.001	70.7%	0.228
	HCW > 97.7 kg	6	−0.262	< 0.0001	0.0%		2	0.174	0.003	0.0%	
	V2 to slaughter < 4.5 w	11	−0.228	< 0.0001	40.9%	0.840	10	0.102	< 0.0001	0.0%	0.126
	V2 to Slaughter ≥4.5 w	21	−0.221	< 0.0001	44.6%		15	0.057	0.003	56.7%	
LW	Peer-reviewed studies	30	2.199	0.007	86.2%	0.402	26	3.049	< 0.0001	73.1%	n.a.
(kg)	Non-peer-reviewed studies	4	0.486	0.796	77.9%		0				
	All comparisons	34	2.022	0.018	90.5%		26	3.049	< 0.0001	73.1%	
	With ractopamine	5	1.423	0.410	77.7%	0.715	4	2.111	< 0.0001	0.0%	0.185
	Without ractopamine	29	2.141	0.022	90.2%		22	3.335	< 0.0001	73.2%	
	HCW < 90.9 kg	12	1.373	0.478	93.3%	0.855	17	2.623	< 0.0001	55.4%	< 0.0001
	HCW 90.9 to 97.7 kg	11	2.138	0.001	27.3%		3	8.076	< 0.0001	70.6%	
	HCW > 97.7 kg	6	2.618	0.029	47.2%		2	−0.259	0.906	14.8%	
	V2 to slaughter < 4.5 w	11	0.964	0.380	41.3%	0.328	10	2.360	< 0.0001	0.0%	0.334
	V2 to Slaughter ≥4.5 w	18	2.486	0.024	91.7%		12	3.847	0.007	82.2%	

IC = immunocastrated; PC = physically castrated; EM = entire male; n = number of comparisons; RMD = raw mean difference; ADG = average daily gain; FCR = feed conversion ratio; LW = live weight; HCW = hot carcass weight; V2 = second vaccination with Improvac®; w = week.
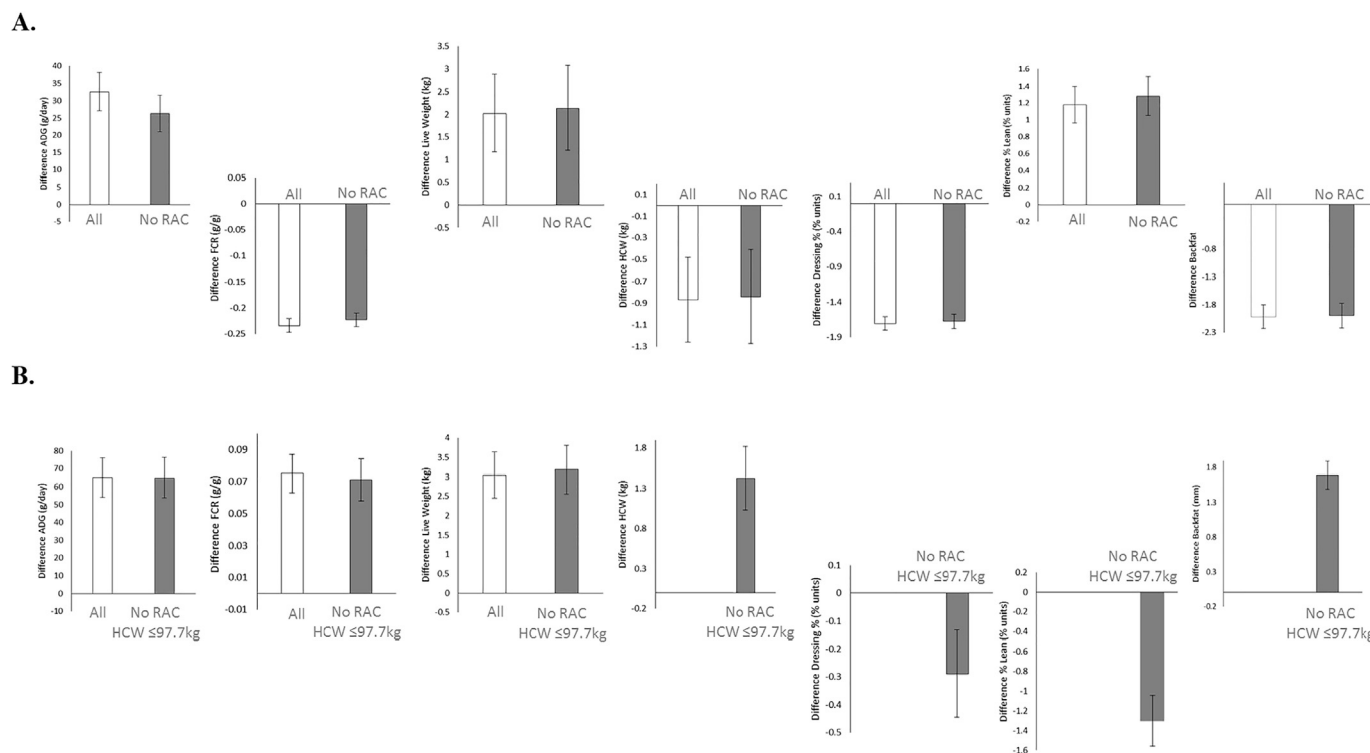
A.

B.

Fig. 1. Results of meta-analyses of growth performance and carcass data as relevant for producers (raw mean differences). A. IC versus PC pigs. Figures present results for all comparisons (All), as well as for a subgroup of studies, which did not use the feed additive ractopamine (No RAC). B. IC versus EM pigs. Figures present results for all comparisons (All), as well as for a subgroup of studies, including pigs with a hot carcass weight ≤ 97.7 kg, which were not fed ractopamine (No RAC; HCW ≤ 97.7 kg).

3.1.2. Comparison of IC pigs versus EM pigs

All studies were published in peer-reviewed journals.

Over all comparisons, the ADG over the entire study period was 65 g per day higher in IC pigs compared with EM pigs ($P < 0.0001$). Although not as pronounced as for the comparison versus PC pigs, there was a trend towards a higher difference in pigs fed ractopamine. Additionally, there were differences between the pork production systems ($P = 0.044$): the difference between IC pigs and EM pigs decreased with increasing HCW, being no longer statistically significant in heavy pigs. Differences in FCR showed that IC pigs consumed on average 0.075 kg more feed per kg body weight gained, consistently across all subgroup analyses. Over all studies, live weight was on average 3 kg higher in IC pigs compared to EM pigs, whereas live weight was similar in heavy pigs (HCW > 97.7 kg). There was a trend towards a higher difference in pigs which were not fed ractopamine as well as in the subgroup of pigs with a time period ≥4.5 weeks between V2 and slaughter (Table 2a and Fig. 1B).

Hot carcass weight was on average 1.4 kg higher in IC pigs compared with EM pigs ($P < 0.0001$). However, the pork production system had a significant impact on this outcome, as the gain was only true in light weight pigs. Dressing percentage was numerically smaller in IC pigs, but the difference was only statistically significant in medium weight pigs ($P = 0.018$). Percentage lean was on average 1.3% units lower in IC pigs compared with EM pigs ($P < 0.0001$); the difference was, however, no longer significant in the subgroup of studies including pigs fed ractopamine. Backfat thickness was approximately 1.7 mm greater in IC pigs compared to EM pigs ($P < 0.0001$). The difference was influenced by ractopamine, as comparisons without the feed additive showed a higher increase in backfat thickness. The difference tended to increase in heavier pigs and pigs slaughtered ≥4.5 weeks after V2 (Table 2b).

3.2. Results from the perspective of the packers

All studies were derived from peer-reviewed articles. In order to avoid too many subgroups with a very low number of studies included, the subgroup analysis on the pork production system was restricted to 2 weight groups for the conventional pork production, i.e. pigs of light and medium weight were combined in one group (HCW ≤ 97.7 kg) and compared with heavy pigs (HCW > 97.7 kg). All pigs destined for high-quality cured products were classified as medium (90.9 kg ≤ HCW ≤ 97.7 kg) or heavy (HCW > 97.7 kg).

3.2.1. Comparison of IC pigs versus PC pigs (conventional pork production)

Over all comparisons IC pigs gained on average 0.21 kg more ham than PC pigs ($P = 0.026$). The significantly higher yield of ham was, however, restricted to comparisons which did not allow ractopamine and pigs with a light to medium HCW. IC pigs gained on average 0.42 kg more shoulder ($P = 0.001$). There was no relevant impact of ractopamine on the difference; however, in heavy pigs the difference was no longer significant. The non-significant differences of ham and shoulder in heavy pigs are based on 2 studies each and the differences between the two subgroups (HCW ≤ 97.7 kg and HCW > 97.7 kg) were not statistically significant.

Over all comparisons, weight of loin was similar, whereas heavy IC pigs gained significantly less loin than PC pigs. The weight of belly was numerically but not statistically significantly lower in IC pigs compared to PC pigs. In the subgroup of studies including ractopamine, however, IC pigs gained statistically significantly less weight of belly. Additionally, there was a trend towards a higher difference in heavy pigs (Table 3).

The overall gain of valuable meat was calculated to 0.63 kg (all studies) or 0.68 kg (only studies not using ractopamine and pigs with HCW ≤ 97.7 kg) and resulted from the statistically significantly higher gain of ham and shoulder. Even when considering the non-significant

Table 2b
Results of meta-analysis of carcass data as relevant for producers (raw mean differences between IC pigs and PC or EM pigs).

		IC versus PC					IC versus EM				
		n	RMD	P-Value	I-squared	P-Value between	n	RMD	P-Value	I-squared	P-Value between
HCW (kg)	Peer-reviewed studies	27	−0.989	0.013	9.4%	0.522	24	1.427	< 0.0001	7.3%	n.a.
	Non peer-reviewed studies	3	−0.587	0.359	75.9%		0				
	All comparisons	30	−0.869	0.026	22.5%		24	1.427	< 0.0001	7.3%	
	With ractopamine	3	−1.042	0.258	11.6%	0.908	3	2.593	0.002	43.7%	0.146
	Without ractopamine	27	−0.838	0.053	26.0%		21	1.233	0.002	0.0%	
	HCW < 90.9 kg	11	−0.132	0.813	0.0%	0.457	17	2.029	< 0.0001	0.0%	0.004
	HCW 90.9 to 97.7 kg	12	−1.231	0.076	43.8%		4	−0.459	0.519	0.0%	
	HCW > 97.7 kg	4	−0.259	0.863	53.1%		0				
	V2 to slaughter < 4.5 w	10	−0.713	0.375	6.7%	0.887	10	1.859	0.002	0.0%	0.276
	V2 to Slaughter ≥ 4.5 w	17	−0.850	0.107	37.0%		11	0.916	0.137	14.5%	
Dressing (% units)	Peer-reviewed studies	23	−1.699	< 0.0001	1.7%	0.733	19	−0.289	0.065	44.7%	n.a.
	Non peer-reviewed studies	1	−1.900	0.001	0.0%		0				
	All comparisons	24	−1.705	< 0.0001	0.0%		19	−0.289	0.065	44.7%	
	With ractopamine	3	−1.869	< 0.0001	0.0%	0.500	0				n.a.
	Without ractopamine	21	−1.676	< 0.0001	6.6%		19	−0.289	0.065	44.7%	
	HCW < 90.9 kg	7	−1.335	< 0.0001	0.0%	0.006	15	−0.109	0.496	27.9%	
	HCW 90.9 to 97.7 kg	11	−2.001	< 0.0001	0.0%		4	−0.707	0.018	53.7%	0.078
	HCW > 97.7 kg	3	−1.441	< 0.0001	0.0%		0				
	V2 to slaughter < 4.5 w	9	−1.656	< 0.0001	20.2%	0.934	9	−0.472	0.106	43.9%	0.325
	V2 to Slaughter ≥ 4.5 w	12	−1.674	< 0.0001	3.3%		10	−0.142	0.383	33.8%	
LMP (% units)	Peer-reviewed studies	22	1.133	< 0.0001	59.1%	0.055	16	−1.302	< 0.0001	52.4%	n.a.
	Non peer-reviewed studies	1	2.030	0.003	0.0%		0				
	All comparisons	23	1.181	< 0.0001	60.0%		16	−1.302	< 0.0001	52.4%	
	With ractopamine	1	0.100	0.677	0.0%	0.003	3	−0.489	0.310	84.7%	0.114
	Without ractopamine	22	1.281	< 0.0001	54.5%		13	−1.342	< 0.0001	24.5%	
	HCW < 90.9 kg	8	1.683	< 0.0001	0.0%	0.399	10	−1.301	< 0.0001	10.4%	0.809
	HCW 90.9 to 97.7 kg	10	1.076	0.002	51.3%		3	−1.344	< 0.0001	65.5%	
	HCW > 97.7 kg	4	1.399	0.023	76.6%		0				
	V2 to slaughter < 4.5 w	8	1.710	< 0.0001	0.0%	0.111	5	−1.489	0.001	26.3%	0.705
	V2 to Slaughter ≥ 4.5 w	14	1.074	< 0.0001	59.3%		8	−1.299	< 0.0001	31.8%	
Backfat (mm)	Peer-reviewed studies	23	−2.011	< 0.0001	30.5%	0.580	22	1.693	< 0.0001	32.3%	n.a.
	Non peer-reviewed studies	1	−2.500	0.025	0.0%		0				
	All comparisons	24	−2.017	< 0.0001	28.1%		22	1.693	< 0.0001	32.3%	
	With ractopamine	2	−1.796	0.001	79.3%	0.856	3	0.885	0.001	25.7%	0.001
	Without ractopamine	22	−1.998	< 0.0001	22.6%		19	1.896	< 0.0001	0.7%	
	HCW < 90.9 kg	8	−2.386	< 0.0001	0.0%	0.153	15	1.725	< 0.0001	0.0%	0.216
	HCW 90.9 to 97.7 kg	11	−1.786	< 0.0001	37.7%		4	2.349	< 0.0001	39.3%	
	HCW > 97.7 kg	3	−1.984	< 0.0001	0.0%		0				
	V2 to slaughter < 4.5 w	8	−2.324	< 0.0001	0.0%	0.341	9	1.517	< 0.0001	2.4%	0.071
	V2 to Slaughter ≥ 4.5 w	14	−1.885	< 0.0001	36.5%		10	2.193	< 0.0001	0.0%	

IC = immunocastrated; PC = physically castrated; EM = entire male; n = number of comparisons; RMD = raw mean difference; HCW = hot carcass weight; LMP = lean meat percentage; V2 = second vaccination with Improvac®; w = week.

differences, i.e. the lower gain of loin and belly, IC pigs still yielded more valuable meat compared with PC pigs (+ 0.42 kg over all studies, + 0.6 kg in studies excluding ractopamine and pigs with HCW ≤ 97.7 kg) (Figs. 2A + B).

3.2.2. Comparison of IC pigs versus EM pigs (conventional pork production)

Over all comparisons the weight of ham was similar between IC pigs and EM pigs. However, within the subgroup of studies allowing the feed additive ractopamine, IC pigs had a greater yield of ham compared with EM pigs (P = 0.004). Gain of shoulder was numerically but not statistically significantly higher over all studies. The difference, however, became statistically significant in studies including pigs fed ractopamine. Heavy pigs gained numerically, but not statistically significantly less shoulder. Gain of loin was significantly higher in IC pigs compared with EM pigs (+ 0.82 kg; P < 0.0001 over all comparisons). Although in heavy pigs the difference was no longer significant, there was only one study included, thus limiting the statistical power. Over all studies, IC pigs gained on average 0.56 kg more belly than EM pigs (P < 0.0001). The additional gain of belly was statistically more pronounced in studies including pigs fed ractopamine.

The overall gain of valuable meat was calculated to 1.39 kg (all studies) or 1.13 kg (studies excluding ractopamine and pigs with HCW ≤ 97.7 kg) and resulted from the statistically significantly higher

gain of loin and belly. The overall gain of valuable meat was also calculated if non-significant differences in the subgroup of studies on pigs with HCW ≤ 97.7 kg (without ractopamine) were included, which were in disfavor for IC pigs (non-significantly less weight of ham). Overall gain was still higher in IC pigs, totaling to 0.94 kg (Fig. 3A + B).

3.2.3. Comparison of IC pigs versus PC pigs (destined for the production of high-quality cured products)

We did not identify any study of pigs destined for the production of high-quality cured products which considered EM pigs as comparator or included the feed additive ractopamine.

Over all weight classes, HCW was 1.78 kg (P = 0.043) lower in IC pigs. In subgroups, the differences were no longer statistically significant, but were based on a small numbers of studies (n = 2 and n = 3). Dressing percentage was on average 2.1% units lower in IC pigs (P < 0.0001) and although the difference tended to increase in heavier pigs, the difference between the subgroups was not statistically significant (P = 0.089).

Over all studies the yield of ham was similar in IC pigs and PC pigs. When considering heavy pigs only, IC pigs gained on average 0.3 kg more ham (P = 0.029), whereas weight of ham was lower in IC pigs of medium weight when compared with PC pigs of the same weight. Backfat was approximately 3 mm smaller in IC pigs (P < 0.0001). IMF

Table 3
Results of meta-analysis of carcass data from conventional pork production as relevant for packers (raw mean differences between IC pigs and PC or EM pigs).

	IC versus PC					IC versus EM				
	n	RMD	*P*-Value	*I*-squared	*P*-Value between	n	RMD	*P*-Value	*I*-squared	*P*-Value between
Ham (kg)										
All comparisons	13	0.213	0.026	48.1%		10	0.057	0.705	49.1%	
With ractopamine	3	−0.050	0.213	62.2%	0.002	3	0.574	0.004	0.0%	0.001
Without ractopamine	10	0.223	0.004	0.0%		7	−0.182	0.070	0.0%	
HCW ≤ 97.7 kg	8	0.245	0.009	12.3%	0.810	6	−0.186	0.068	0.0%	0.821
HCW > 97.7 kg	2	0.133	0.729	0.0%		1	−0.040	0.950	0.0%	
Shoulder (kg)										
All comparisons	13	0.415	0.001	55.6%		10	0.391	0.052	41.6%	
With ractopamine	3	0.411	0.001	0.0%	0.037	3	0.590	0.035	0.0%	0.369
Without ractopamine	10	0.400	0.016	57.4%		7	0.348	0.200	55.5%	
HCW ≤ 97.7 kg	8	0.435	0.025	66.6%	0.712	6	0.458	0.103	56.2%	0.150
HCW > 97.7 kg	2	0.254	0.493	0.0%		1	−0.660	0.336	0.0%	
Loin (kg)										
All comparisons	13	−0.030	0.593	11.3%		10	0.823	< 0.0001	69.6%	
With ractopamine	3	−0.299	0.443	0.0%	0.422	3	0.904	< 0.0001	19.2%	0.107
Without ractopamine	10	−0.042	0.590	29.5%		7	0.758	0.022	75.5%	
HCW ≤ 97.7 kg	8	−0.002	0.959	10.4%	0.030	6	0.717	0.049	78.9%	0.355
HCW > 97.7 kg	2	−0.809	0.033	0.0%		1	1.140	0.096	0.0%	
Belly (kg)										
All comparisons	13	−0.176	0.171	53.9%		10	0.562	< 0.0001	30.7%	
With ractopamine	3	−0.367	0.019	3.7%	0.511	3	0.928	< 0.0001	0.0%	0.039
Without ractopamine	10	−0.150	0.349	61.7%		7	0.436	0.001	20.5%	
HCW ≤ 97.7 kg	8	−0.078	0.668	67.6%	0.229	6	0.413	0.008	29.4%	0.495
HCW > 97.7 kg	2	−0.606	0.051	0.0%		1	0.600	0.040	0.0%	

IC = immunocastrated; PC = physically castrated; EM = entire male; n = number of comparisons; RMD = raw mean difference; HCW = hot carcass weight.

A.
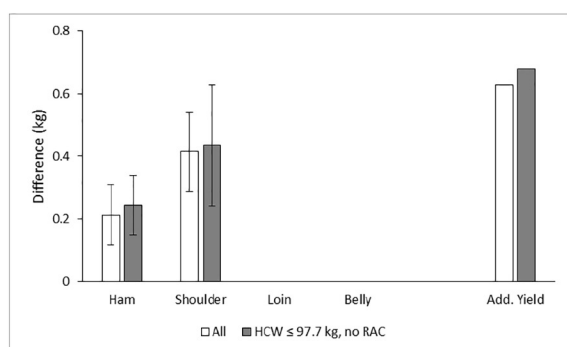
B.
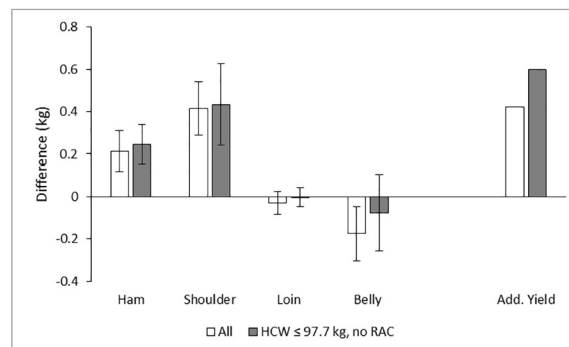
Fig. 2. Differences in weight of primal cutouts (valuable meat) between IC versus PC pigs. The figures present results for all comparisons as well as for a subgroup of studies with light and medium weight pigs (HCW ≤ 97.7 kg), which were not fed ractopamine (no RAC). A. Considering statistically significant differences only. B. Considering statistically significant and non-significant differences, the latter only if in disfavor for IC pigs (less gain), thereby representing an extremely conservative approach.

was also lower (− 0.30% units), but the difference did not reach statistical significance (Table 4).

Mean values of backfat thickness and IMF for IC pigs and PC pigs were extracted from each study. Backfat thickness was 50.1 mm (IC pigs) and 52.8 mm (PC pigs) in one study on Iberian pigs (Martinez-Macipe et al., 2016), in the other studies using various breeds destined for the production of high-quality cured products, backfat was between 23.3 mm and 27.6 mm (IC pigs) and between 26.4 mm and 32.0 mm (PC pigs). In Iberian pigs IMF was 7.0% (IC pigs) and 9.1% (PC pigs). The other studies reported percentages of IMF between 3.7% and 4.4% for IC pigs and between 3.9% and 5.3% for PC pigs.

3.3. Results relevant from both perspectives: Boar taint analyses

3.3.1. Number of pigs exceeding thresholds of detection

A comparably high proportion of studies was derived from non-peer-reviewed sources (between 20% and 50%, depending on the comparison and boar taint compound). Results were not different

between the subgroups of studies derived from peer-reviewed sources and those published elsewhere (data not shown). Therefore, results are presented for all studies (Table 5).

Compared with PC pigs, IC pigs have a similar risk ($P > 0.05$) of exceeding the thresholds of detection for skatole and androstenone (intermediate and high threshold). On the contrary, the risk was statistically significantly higher in EM pigs ($P < 0.0001$) compared with IC pigs (Table 5).

3.3.2. Results of sensory assessment of pork meat

Only descriptive analysis was used to evaluate differences in the sensory assessment between pork from IC pigs and PC or EM pigs. All studies were included regardless of their source (peer-reviewed source and non peer-reviewed source) and no subgroup analysis was conducted.

Results of the sensory assessment are shown in Table 6. Consumer and expert panels have rated meat from IC pigs comparable to that from PC pigs. For 4 parameters (consumer panels: odor and flavor; expert
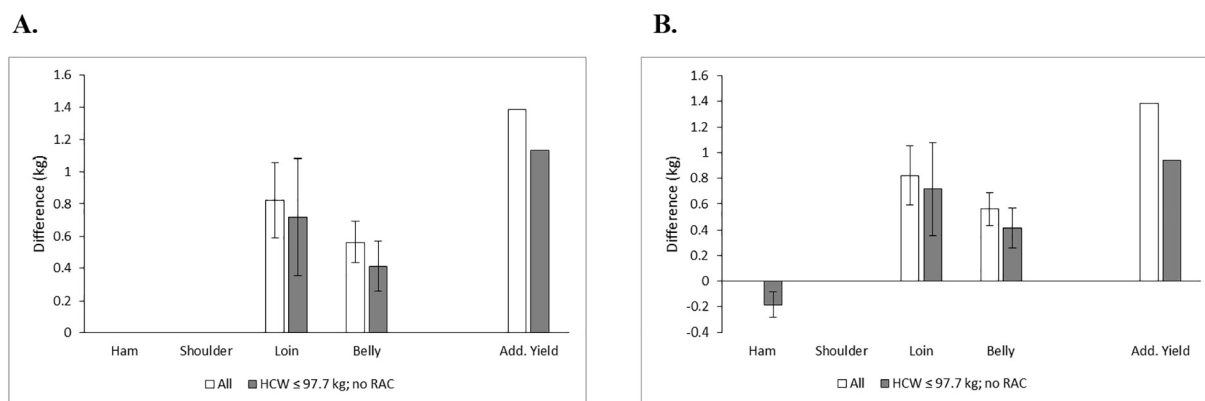
A.

B.

Fig. 3. Differences in weight of primal cutouts (valuable meat) between IC versus EM pigs. The figures present results for all comparisons as well as for a subgroup of studies with light and medium weight pigs (HCW ≤ 97.7 kg), which were not fed ractopamine (no RAC). A. Considering statistically significant differences only. B. Considering statistically significant and non-significant differences, the latter only, if in disfavor for IC pigs (less gain), thereby representing an extremely conservative approach.

Table 4
Results of meta-analysis of carcass data from pigs destined for the production of high-quality cured products as relevant for packers (raw mean differences between IC pigs and PC pigs).

		IC versus PC			
	n	RMD	*P*-Value	*I*-squared	*P*-Value between
HCW (kg)					
All comparisons	5	−1.780	0.043	0.0%	
Medium carcass	2	−2.488	0.083	0.0%	0.533
Heavy carcass	3	−1.356	0.223	0.0%	
Dressing (% units)					
All comparisons	5	−2.121	< 0.0001	9.5%	
Medium carcass	2	−1.800	< 0.0001	0.0%	0.089
Heavy carcass	3	−2.567	< 0.0001	92.0%	
Ham (kg)					
All comparisons	5	0.083	0.695	73.2%	
Medium carcass	2	−0.371	0.032	64.8%	0.002
Heavy carcass	3	0.297	0.029	30.0%	
Backfat (mm)					
All comparisons	5	−2.965	< 0.0001	0.0%	
Medium carcass	2	−2.767	0.001	0.0%	0.757
Heavy carcass	3	−3.128	< 0.0001	0.0%	
IMF (%)					
All comparisons	5	−0.297	0.083	23.4%	
Medium carcass	2	−0.161	0.390	0.0%	0.394
Heavy carcass	3	−0.403	0.059	54.9%	

IC = immunocastrated; PC = physically castrated; EM = entire male; n = number of comparisons; RMD = raw mean difference; HCW = hot carcass weight; IMF = intramuscular fat.

panels: flavor and overall acceptability/liking) the majority of studies revealed a similar rating between meat from IC pigs and PC pigs, whereas the number of studies in favor and disfavor for IC pigs was equal. For the remaining two parameters (consumer panels: overall acceptability/liking; expert panels: odor) ratings were either equal or numerically in favor for meat from IC pigs. Compared with meat from

Table 6
Descriptive results of sensory assessments of pork meat from IC, PC, or EM pigs. Studies were classified according to their comparative rating, i.e. if meat from IC pigs was rated better, equal, or worse than meat from comparator.

	Odor		Flavor		Overall Acceptability / Liking	
	IC vs. PC	IC vs. EM	IC vs. PC	IC vs. EM	IC vs. PC	IC vs. EM
Consumer Panels:						
Number of panelists: Total: 1813 (Calculated mean: 130)						
Number of different pigs used as sources of pork meal: Total: 738 (Calculated mean: 46)						
No. of comparisons	13	8	14	7	10	7
IC Pigs rated better	2	4	2	3	2	2
IC Pigs rated equal	9	4	10	4	7	5
IC Pigs rated worse	2	0	2	0	1	0
Expert Panels:						
Number of panelists: Total: 118 (Calculated mean: 8)						
Number of different pigs used as sources of pork meal: Total: 1289 (Calculated mean: 81)						
No. of comparisons	13	10	13	9	2	2
IC Pigs rated better	1	7	0	5	0	1
IC Pigs rated <u>equal</u>	12	3	13	4	2	1
IC Pigs rated <u>worse</u>	0	0	0	0	0	0

IC = immunocastrated; PC = physically castrated; EM = entire male.

EM pigs, meat from IC pigs was always rated better or at least equal.

There were no relevant differences between the ratings of the three parameters evaluated (odor, flavor, and overall acceptability/liking).

In overall and subgroup analyses, as well as analyses of boar taint compounds, heterogeneity was broadly varying, and I^2 values were calculated between 0% and 95.9% (Tables 2–5).

4. Discussion

The purpose of our study was not only to update previous meta-

Table 5
Results of meta-analysis, calculating the risk differences between the number of IC pigs and PC or EM pigs exceeding the defined thresholds of detection for skatole and androstenone.

	IC versus PC Pigs				IC versus EM Pigs			
Threshold of detection	n	Risk Difference	*P*-Value	*I*-Squared	n	Risk Difference	*P*-Value	*I*-Squared
Skatole ≥ 0.2 μg/g fat	17	0.004	0.178	0.0%	20	−0.095	< 0.0001	79.5%
Androstenone ≥ 0.5 μg/g fat	12	0.003	0.147	0.0%	8	−0.574	< 0.0001	89.5%
Androstenone ≥ 1.0 μg/g fat	18	0.000	0.805	0.0%	15	−0.306	< 0.0001	95.9%

IC = immunocastrated; PC = physically castrated; EM = entire male; n = number of comparisons.

analyses with more recently published papers, but also to target the analyses towards the two important stakeholder groups of producers and packers. Additionally, we aimed to evaluate the impact of pre-defined production management aspects on the outcomes, specifically the use of ractopamine, different pork production systems (raising light, medium, or heavy pigs), and the time period between V2 and slaughter.

All (overall and subgroup) analyses included studies from peer-reviewed and non-peer-reviewed sources, thereby being in accordance with previous meta-analysis (Batorek et al., 2012a). Another meta-analysis in this area, however, considered only peer-reviewed articles (Dunshea et al., 2013). For reasons of comparability, we firstly conducted a subgroup analysis evaluating the consistency of results derived from peer-reviewed and non peer-reveiwed sources. As no statistically significant differences existed, our results can be compared with other meta-analyses, regardless of their eligibility criteria in this respect. Additionally, the inclusion of all comparisons resulted in a higher number of studies and associated statistical power.

Our analyses from the perspective of the producers included growth performance parameters and carcass data. Compared with PC pigs, IC pigs have a higher ADG, improved FCR, higher live weight, lower dressing percentage, a higher percentage lean and smaller backfat thickness. These findings are in line with previous meta-analyses (Dunshea et al., 2013 and Batorek et al., 2012a). Additionally, HCW was significantly lower in our analyses including all comparisons, whereas Dunshea et al. (2013) and Harsh et al. (2017) calculated non-significant differences between IC pigs and PC pigs, being aligned with our results from subgroup analyses.

The results of our meta-analyses comparing IC pigs with EM pigs are also well confirmed by previous meta-analyses: a higher ADG, FCR, live weight, and HCW, as well as a lower percentage lean and thicker backfat have also been reported by Dunshea et al. (2013) and Batorek et al. (2012a). In our analyses as well as in the analysis published by Batorek et al. (2012a), dressing percentage was numerically but not statistically significantly lower in IC pigs compared with EM pigs, whereas Dunshea et al. (2013) found a statistically significant reduction.

Our analyses of studies on conventional pork production as relevant from the perspective of the pork packing industry were focusing on the gain of valuable meat, which was defined according to Harsh et al. (2017) as ham, shoulder, loin, and belly. Over all studies in our analysis, IC pigs gained a significantly higher weight of ham and shoulder compared to PC pigs, and a similar weight of loin and belly. These results correspond well with outcomes reported by Batorek et al. (2012a), although the numerically higher weight of shoulder was not statistically significant in their meta-analysis. Harsh et al. (2017) also reported a higher weight of whole ham although it did not reach statistical significance. Our analysis, however, was based on a higher number of comparisons ($n = 13$), as Harsh et al. (2017) only considered studies performed according to US conditions ($n = 6$ and $n = 7$, for PC pigs and IC pigs, respectively) and Batorek et al. (2012a) included studies until mid of 2011 ($n = 4$ to 7, depending on the primal cutout). A higher gain of loin and belly in IC pigs compared with EM pigs has also been found by Batorek et al. (2012a), although the numerically higher weight of loin was not statistically significant, which might also be due to the lower number of studies included at the time of their analysis.

When summing up the statistically significant differences in weight of the primal cutouts, IC pigs yielded more valuable meat than PC pigs and EM pigs. In an extremely conservative approach, we additionally considered non-significant differences which were in disfavor for IC pigs, while ignoring the favorable non-significant ones. Even in these extreme conservative analyses, IC pigs yielded more valuable meat compared to PC pigs or EM pigs.

This finding is the more important for the pork packing industry, as it overrules the potentially perceived negative impact of a lower dressing percentage in IC pigs compared with PC pigs. Despite the lower dressing percentage, IC pigs return more valuable meat than PC pigs.

The difference in dressing percentage in our study was, however, calculated from studies included for the perspective of the producers, and therefore derived from a higher number of studies. However, this parameter had also been calculated for the data set used for the perspective of the packers (studies not using ractopamine), totaling to a 1.615% units lower carcass yield in IC pigs compared with PC pigs (Mah et al., 2018). This value corresponds well with the dressing percentage estimated from studies included for analyses from the perspective of the producers (-1.676% units in studies without ractopamine), thus also confirming the validity of the dataset used for analyses from packers's perspective, which was based on a lower number of studies.

To our knowledge we have conducted the first meta-analysis of studies which considered pigs specifically raised for the production of high-quality cured products, thereby focusing on HCW, dressing percentage, weight of ham, backfat thickness and IMF.

Dressing percentage and HCW were significantly lower in IC pigs compared to PC pigs. The non-significant results for HCW in the subgroups of medium and heavy carcasses must be interpreted with caution because of the low numbers of studies included ($n = 2$ and $n = 3$), which limit the statistical power.

Across all weight classes, gain of ham was similar. When looking at the different weight classes however, an opposite effect is observed: medium weighted IC pigs (HCW ≤ 97.7 kg) yielded significantly less ham, whereas heavy IC pigs (HCW > 97.7 kg) gained on average 0.3 kg more ham compared with PC pigs of the same weight class. Backfat thickness and IMF were lower in IC pigs but still fulfilled the minimum requirements as defined for high-quality cured products, i.e. backfat ≥ 20 mm and IMF $\geq 2.5\%$ (Morales et al., 2011a). Accordingly, it can be stated that immunocastration with Improvac® is a suitable alternative to physical castration of pigs raised for the production of high-quality cured products when raised to heavy weight, which is the preferred weight class for the dry-cured industry (Morales et al., 2011a).

For boar taint analyses we did not compare absolute levels of skatole or androstenone in fat, as any difference in level is of no relevance for the consumers, as long as the threshold of detection, i.e. the minimum level of compound in fat to be recognized by average consumers, is not exceeded. Instead, we considered the number of pigs exceeding the respective threshold, being the most meaningful assessment (Allison et al., 2009b). We found that the risk of exceeding the threshold of detection is significantly higher in EM pigs compared to IC pigs, whereas the risk was similarly low in IC pigs and PC pigs. This is the more important as 2 non-responder IC pigs were included in each of 2 studies (Škrlep et al., 2012; Jaros et al., 2005). These pigs were clinically identified as having not responded to immunization against GnRF, but were included in the analyses.

The meta-analysis published by Batorek et al. (2012a) reported lower levels of both boar taint compounds in IC pigs compared with EM pigs, but higher skatole levels in fat of IC pigs compared with PC pigs. However, it is unknown whether the observed higher level of skatole in IC pigs has any potential impact for consumers, as results have not been reported in relation to the threshold of detection.

For the evaluation of the sensory assessment of pork meat we followed a similar approach as used by Allison et al. (2009a), i.e. the categorization of studies according to their relative rating. For each study it was recorded if meat from IC pigs was rated better, equally, or worse than meat from PC or EM pigs.

This approach, however, has the disadvantage that it only allows for a descriptive analysis. The results must be interpreted with caution, because studies were not weighted, as no general agreement was found regarding the weighting basis (number of panelists or number of different pigs used as source of samples). For example, weighting by number of panelists would relevantly increase the power of consumer panels (which use more panelists than expert panels), whereas experts can be regarded as more sensitive as they were selected on basis of

androstenone sensitivity and specifically trained. On the other hand, weighting by number of pigs would lead to an arbitrary weighting, as studies using samples from a high number of different pigs rated by a small number of panelists would be weighted much higher than a study using numerous consumer panelists rating samples from a limited number of pigs. Accordingly, it cannot be stated that the same number of studies being advantageous (rated better) or disadvantageous (rated worse) for IC pigs compared to PC pigs corresponds to equality. Nevertheless, there were no obvious differences between the rating of meat from IC pigs and PC pigs. This is also in line with results from a previous study (Allison et al., 2009a), and also confirms our results from objective measurements of levels of boar taint compounds. On the other hand, there was no study rating meat from IC pigs worse than meat from EM pigs, as meat from IC pigs was consistently rated equally or better. As a result, we can conclude that meat from IC pigs is preferred over meat from EM pigs. There were no relevant differences between the assessments of consumer or expert panels, thereby confirming the relevance of results for the consumers as well as the accuracy of rating. There were no differences between the three parameters tested (odor, flavor, and overall liking). Whereas odor and flavor are mainly focusing on boar taint, overall acceptability or liking also considers other factors potentially impacting consumer's preference, such as juiciness, tenderness, and toughness (Allison et al., 2009a).

Altogether, we can conclude from objective measurements and subjective sensory assessments that there is no higher risk of boar taint in IC pigs compared with PC pigs, whereas the risk is significantly higher in EM pigs.

Results from our analyses including all comparisons are well in line with results published by others and can therefore be regarded as valid. However, to answer the predefined research questions we have also conducted several subgroup analyses.

First of all, we have evaluated the impact of feeding ractopamine on the differences between IC pigs and comparators. From the perspective of the producers, ractopamine increased the difference in ADG, i.e. the higher ADG is even more pronounced in IC pigs when compared with PC pigs or EM pigs. There was a trend towards a reduced difference in live weight when fed ractopamine, and live weight was only statistically significantly higher in IC pigs compared with PC pigs when ractopamine was not administered. Percentage lean was significantly different (higher percentage lean compared to PC pigs and lower percentage lean compared to EM pigs) only when not feeding ractopamine. Conversely, when fed ractopamine there was no longer a difference between IC pigs and PC or EM pigs in percentage lean. In contrast, Martins et al. (2012) reported that feeding ractopamine increases pork lean quantity especially for IC pigs, i.e. the increase in lean is more pronounced in IC pigs than in PC pigs. In our analysis, however, the increase in percentage lean was nullified when ractopamine was fed. These subgroup results, however, were based on one study (versus PC pigs) or 3 studies (versus EM pigs) only and has to be interpreted with caution. Further research is warranted to draw final conclusions on the impact of feeding ractopamine on the differences between IC pigs and PC or EM pigs regarding the percentage lean meat.

From the perspective of the pork packing industry, ractopamine also has a relevant impact. When feeding ractopamine the weight of ham of IC pigs is no longer higher compared to PC pigs, whereas it significantly increases compared to EM pigs. Therefore, feeding ractopamine offsets the advantage of a higher gain in ham compared to PC pigs, but contrarily results in a higher weight of ham compared to EM pigs which otherwise does not exist. The lower weight of belly in IC pigs compared to PC pigs became statistically significantly when feeding ractopamine, whereas the higher gain of belly compared to EM pigs became also more pronounced.

Subgroup analyses on the impact of the pork production system (light, medium, or heavy pig production) and the time period between V2 and slaughter were run on studies excluding ractopamine, thus allowing the transferability of results to all countries where the feed

additive is not licensed. However, these results cannot be immediately transferred to industry feeding practices which use ractopamine.

From the perspective of the producers, raising heavier pigs resulted in a further increase of live weight in IC pigs compared to PC pigs. Compared with EM pigs the difference in ADG decreased with increasing weight of pigs, and live weight and HCW were only higher in light and medium (live weight) or light (HCW) pigs. Accordingly, these advantages reported for IC pigs compared to EM pigs are offset in heavy pig production systems.

From the perspective of packers, the pork production system had no relevant impact when comparing IC pigs with EM pigs. On the contrary, compared to PC pigs the higher gain of ham and shoulder is valid only in light to medium pigs (HCW ≤ 97.7 kg), whereas in heavy pigs, the lower gain of loin in IC pigs became statistically significant. Accordingly, the advantage reported for IC pigs compared to PC pigs (higher gain of valuable meat) seems to be true only in pigs with a HCW ≤ 97.7 kg. However, results need to be interpreted with caution as only two studies were included in the subgroup of heavy pigs.

We also evaluated the impact of a short (< 4.5 weeks) versus long (≥ 4.5 weeks) period between V2 and slaughter on the comparative results as relevant for the producers. The cutoff time used in our study for the definition of the two subgroups was set at 4.5 weeks. The time was chosen as the mean time between second vaccination and slaughter over all studies was < 5 weeks (4.88 weeks). Therefore, a period of 4.5 weeks seemed to be a rational and practical approach.

Compared to PC pigs live weight of IC pigs was only statistically significantly higher if the time period between V2 and slaughter was ≥ 4.5 weeks. There was a trend towards a smaller difference between IC pigs and PC pigs in percentage lean meat and backfat thickness with an increasing time between V2 and slaughter. Compared to EM pigs there was a trend towards a higher difference in live weight and greater difference in backfat thickness with an increasing time period. These trends are not unexpected, as with an increasing time between V2 and slaughter the time increases where IC pigs behave similarly to barrows, thereby reducing the differences in percentage lean and backfat compared to PC pigs. For the same reason the difference in backfat compared to EM pigs increases.

Our study has limitations. First of all, our meta-analysis was not based on a systematic literature search and review, but used as source an existing database developed and updated regularly by the company marketing Improvac®. The completeness of the database was, however, verified by manually reviewing bibliographies and review articles. No further comparison was identified, therefore we considered the database as complete.

Randomization and blinding were not considered as inclusion criteria. Although most studies included for the analyses of performance and carcass data reported randomization, the kind of randomization was not described and the appropriateness of randomization could not be assessed. There were, however, no significant differences between the outcomes of studies published in peer-reviewed journals and studies published elsewhere and it can be expected that non-randomization is of more concern in studies published outside of the traditional academic publishing and distribution channels. Thus we believe that the consideration of all studies regardless of the reporting of randomization did not cause a fundamental bias. Blinding was not applicable, because of the physical differences between PC, IC, and EM pigs.

Some subgroup analyses have limitations, as a fixed-effect model was used to calculate the mean effect size when the number of studies was ≤ 3. In that case, also a fixed-effect model was used to estimate the differences between subgroups. The preferred model to evaluate treatment effects would have been a random-effects model for the mean effect size analysis and a mixed-effects model for the analyses between subgroups (based on random-effects model within subgroups), as the random-effects model accounts for differences between studies due to study design, pig population, feeding strategies, housing, etc.. It results, however, in incorrect point estimates and confidence intervals, when

the number of studies is small (Borenstein et al., 2009). Accordingly, current effect sizes are based on different models, an approach which has been used in other meta-analysis as well (De la Cruz et al., 2017). Nevertheless, subgroup analyses based on 3 or less comparisons need to be interpreted with caution.

Heterogeneity was estimated using I^2 statistics. Although the Q statistic is also traditionally considered as valid for estimating heterogeneity between studies, researchers have argued that meta-analysis of data from studies that are both clinically and methodologically diverse should indeed result in heterogeneity reflected in the Q statistic, thereby limiting the meaningfulness of this measure. Therefore and in accordance with other meta-analyses (De la Cruz et al., 2017; Batorek et al., 2012a) the I^2 statistic was calculated according to Higgins et al. (2003), which describes the percentage of total variation across studies which is due to true heterogeneity rather than chance. Heterogeneity varied broadly in our analyses and estimates of I^2 were calculated between zero and 95.9%. Thereby, heterogeneity was similar to results from previous meta-analysis (Batorek et al., 2012a), where I^2 was reported to be between zero and 96%. Heterogeneity was still high in several subgroup-analyses, hence differences between studies could not be totally explained by those aspects addressed in our subgroup analyses. However, a high heterogeneity was not an unexpected finding, as very different studies were included in the meta-analyses, using pigs of different breeds, different feed and housing systems. Nevertheless, with the inclusion of different studies reflecting very different pig production conditions, we can expect our results to be valid over a broad range of pig production conditions.

As a final point, it should be noted that this meta-analysis approach automatically incorporates a limitation common to the comparative studies it is based on. To limit the number of variables the experimental groups being compared are often managed in the same way and fed the same diet. This is correct scientific procedure, but ignores the fact that nutritional requirements in particular, are different for the different types of animal. Optimal growth performance for IC pigs can only be obtained by giving a specifically formulated diet, which was rarely done. The results presented, therefore, may not represent the true potential of the approach.

5. Conclusion

Based on our analyses the pre-defined research questions can be answered as follows:

1. Meta-analyses of studies comparing IC pigs with PC or EM pigs confirmed previously published advantages of IC pigs from the perspective of the producers. When feeding ractopamine the difference in ADG becomes even more favorable for IC pigs. Additionally, the producers can tailor the pork meat to different market situations by varying the time between 2nd vaccination and slaughter.

2. Despite their lower dressing percentage, IC pigs are leaner and yield on average more valuable meat compared to PC pigs. Compared to EM pigs, light and medium IC pigs have a lower percentage of lean meat but gain more valuable meat. Meta-analyses of studies comparing IC and PC pigs raised for the production of high-quality cured products showed that immunocastration is a suitable alternative to physical castration, as IC pigs still fulfill the requirements on backfat thickness and IMF. Additionally, heavy-weight IC pigs yield more ham despite a lower HCW and dressing percentage.

3. Immunocastration effectively avoids boar taint, which has been assessed using objective measurements of boar taint compounds as well as subjective sensory evaluations.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rvsc.2018.06.002.

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